ROD-PINCH DIODE DEVELOPMENT FOR SHORT-PULSE RADIOGRAPHY USING EXTENDED-LENGTH CATHODES *

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Abstract

Rod-pinch diodes utilize a small-diameter anode rod extending through and beyond the plane of a thin annular cathode.[1] At low voltage (< 1 MV) and short pulse duration (< 20 ns), it is difficult for the space-charge-limited current (SCL) to exceed the critical current necessary for electron beam self-pinching using cathodes thinner than the anode-cathode gap spacing. Because the SCL is proportional to the cathode length and the critical current is independent of it, we have studied multiple-disk, extended-length cathodes for the purpose of achieving critical current early in the pulse. Experiments were conducted on the TriMeV facility at 0.8 to 1.2 MV and 20 to 40 kA with a 15-ns pulse duration. The cathode radius was typically 4 mm with cathode lengths varying from 3 mm to 3 cm. The anode radius was 0.25 mm. As expected, the longer cathodes achieved critical current earlier in the pulse and continued to operate at critical current for the pulse duration. Source diameters measured in the forward direction were about 0.5 mm with doses 1 m from the source in the 0.3- to 0.5-Roentgen range.

I. INTRODUCTION AND THEORY

A large data base of rod-pinch-diode results now exists for voltages between 1.0 and 2.5 MV with typical 50- to 70-ns FWHM pulse durations.[2,3] Use of the rod-pinch diode for x-ray radiography provides substantial improvement over previously available sources [4,5]. This paper will concentrate on a rod-pinch radiography source that was developed to operate at less than 1 MV with a pulse duration of less than 20 ns. This rod-pinch diode was designed to be driven by a compact Marx generator[6] being developed by LLNL and was tested on the Bechtel-Nevada TriMeV pulser[7]. PIC simulations using the MAGIC 2D code were carried out to design the diode, with emphasis on 2D edge effects.

The simulation results shown in Fig. 1 illustrate the geometry and electron flow in the rod-pinch diode where a cylindrical anode passes through and beyond a hole in an annular cathode. The electron flow progresses from radially incident space-charge-limited flow at low voltages (Fig. 1a), to weak pinching at higher voltages where the electrons start to approach the anode at grazing incidence (Fig. 1b), to strongly-pinched self-magnetically-limited flow at the highest voltages where the electrons, aided by anode ions, flow to the tip of the rod (Fig. 1c). Early ion turn-on is essential for the electrons to propagate to the rod tip where they create a very small, bright radiographic x-ray source. The ion current fraction can be between 20-40% and increases with the rod length.

The current versus voltage characteristics for this diode are illustrated in Fig. 2 where the circles indicate the PIC simulation results.[8] At low voltage, the diode current follows the SCL current, $I_{SCL} \sim V^{3/2}$. At higher voltages, the diode current smoothly transitions to the critical current, $I_{crit} \sim V$. Aside from the voltage dependence, the diode impedance depends only on the geometry in the vicinity of the cathode. Also, the effective cathode length

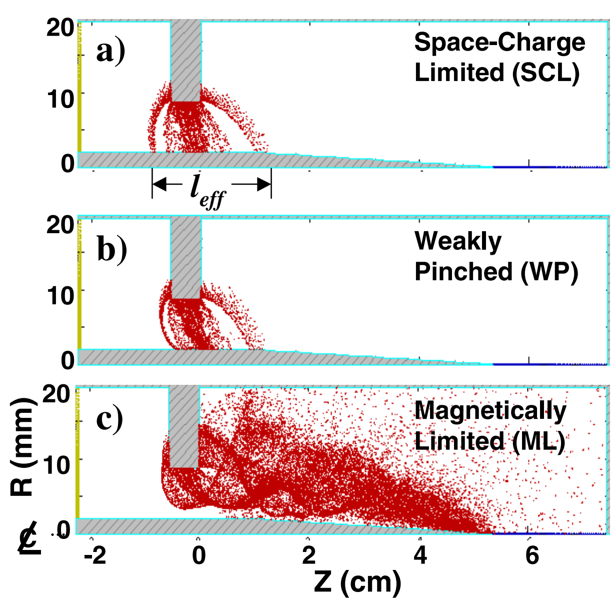

Figure 1. Electron flow patterns.

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14. ABSTRACT

Rod-pinch diodes utilize a small-diameter anode rod extending through and beyond the plane of a thin annular cathode.[1] At low voltage (< 1 MV) and short pulse duration (< 20 ns), it is difficult for the space-chargelimited current (SCL) to exceed the critical current necessary for electron beam self-pinching using cathodes thinner than the anode-cathode gap spacing. Because the SCL is proportional to the cathode length and the critical current is independent of it, we have studied multipledisk, extended-length cathodes for the purpose of achieving critical current early in the pulse. Experiments were conducted on the TriMeV facility at 0.8 to 1.2 MV and 20 to 40 kA with a 15-ns pulse duration. The cathode radius was typically 4 mm with cathode lengths varying from 3 mm to 3 cm. The anode radius was 0.25 mm. As expected, the longer cathodes achieved critical current earlier in the pulse and continued to operate at critical current for the pulse duration. Source diameters measured in the forward direction were about 0.5 mm with doses 1 m from the source in the 0.3- to 0.5-Roentgen range.

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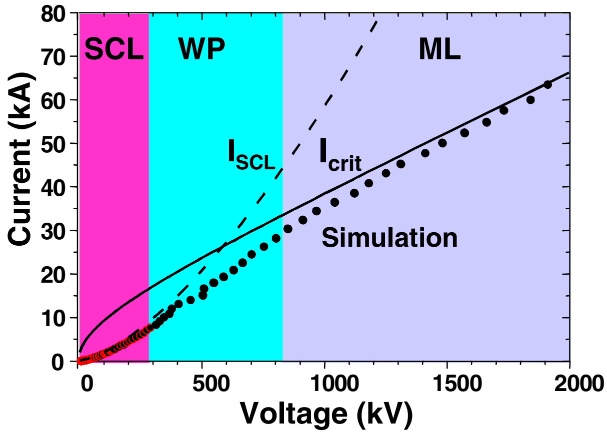

Figure 2. Current versus voltage characteristics for a rod-pinch diode. The circles are PIC simulation results.

during the SCL phase, l_{eff} in Fig. 1a, is approximately equal to the cathode thickness plus twice the AK gap.

The non-relativistic form for the SCL current appropriate for this cylindrical diode geometry without ion emission was first derived by Langmuir and Blodgett[9] and is given by $I_{LB} = I_\alpha \frac{2\sqrt{2}}{9}\frac{l}{R_A \kappa^2} U_0^{3/2}$, where $I_\alpha = m_e c^3/e \cong 17$ kA, $U_0 = eV/m_e c^2$ is the electron energy normalized to the electron rest mass energy, c is the speed of light in vacuum, l is the cathode length, and κ^2 is a function of R_C/R_A, the ratio of cathode to anode (rod) radius. Agreement with simulation is achieved by replacing l with l_{eff}, an effective length that includes edge effects. The presence of ions increases the electron current by a factor of 1.86 for the planar case and up to a factor of 4 for $R_C/R_A = 20$.[2]

In Fig. 3a, 1D analytical solutions are shown to agree with 1D PIC simulations, demonstrating that the bipolar SCL current enhancement factor, I_e/I_{LB}, increases from the planar value of 1.86 for large R_C/R_A. This enhancement is due to the maximum electric field shifting towards the anode for large aspect ratio [2]. Transit time arguments[10] based on space charge balance in the diode ($Q_e = Q_i$) indicate that I_i/I_e is proportional to the ratio of the average ion velocity, v_i, to the average electron velocity, v_e. For large R_C/R_A, the electric field profile increases v_i and decreases v_e, thus increasing I_i/I_e (Fig. 3b). This increase in I_i leads to enhanced ion space charge near the cathode, increasing the bipolar electron current, I_e (Fig. 3a). This current enhancement at large R_C/R_A helps the diode approach critical current at even lower voltages.

The critical current in cylindrical geometry is given by I_{crit} (kA) = $8.5\alpha(\gamma^2-1)^{1/2}/\ln(R_C/R_A)$.[11] It is independent of length, depends only on R_C/R_A, and has an almost linear dependence on voltage at higher voltages. For the pure electron case, $\alpha = 1.45$. With ions, α increases from 1.6 for $R_C/R_A \sim 1$ to about 3 for $R_C/R_A \sim 16$.[2,8] The long electron path length along the rod compared to the AK gap spacing, $D = R_C - R_A$, can lead to large ion current

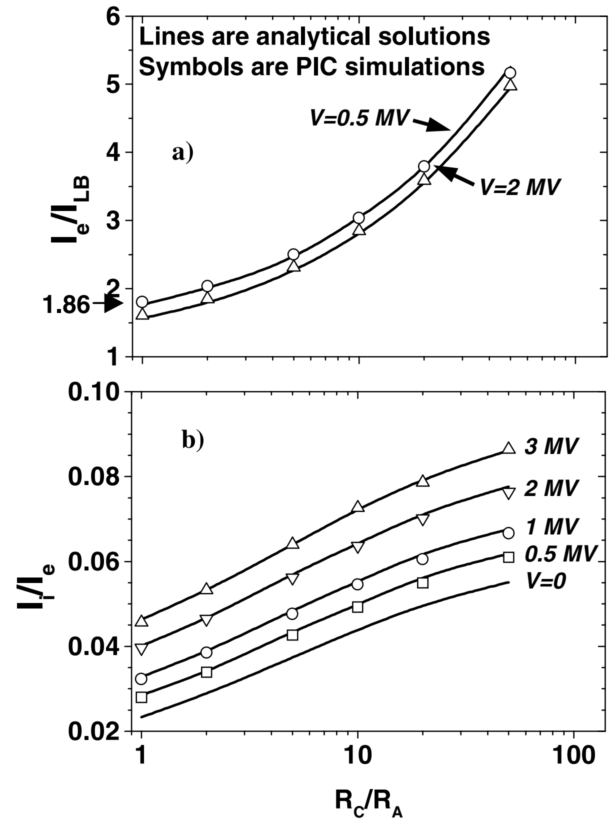

Figure 3. a) Ratio of electron current to Langmuir Blodgett current as a function of R_C/R_A when ions are present. b) Ratio of ion to electron current as a function of R_C/R_A.

fractions for long rods.[2] PIC simulations quantitatively support the length and radius scaling predicted by the SCL and critical current equations.[8]

Cathodes for short-pulse radiography were designed using 2D PIC codes to determine the minimum spacing required for a pair of thin cathode disks to act independently. For a single $l = 1$ mm-thick disk in SCL flow, PIC simulation results agree with the analytic SCL flow solutions when $l_{eff} = l + 2D$. If the mm-thick cathode is divided into two 0.5-mm thick cathodes separated by 5D (see Fig. 4a), the diode current nearly doubles, i.e. $l_{eff} = l + 4D$. Figure 4b shows the variation of l_{eff}/D with S/D, for other separations S. Most of the current enhancement is achieved when S is about 2D. In general, multiple thin cathode disks with S > 2D will increase the current during the SCL phase proportional to the number of disks. If the spacing S < 2D, the electron-flow patterns between disks merge on the anode, and l_{eff} is roughly 2D plus the total distance between the first and last cathode. We speculate that using mostly-hollow, multi-disk cathodes provides a reduced impedance collapse compared to a solid long cathode because a longer time is required for the expanding cathode and anode plasmas to merge.

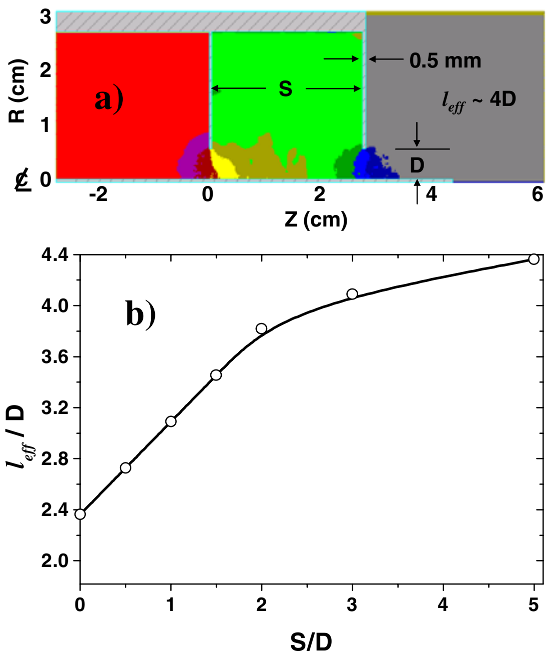

Figure 4. a) Current flow contours (0.4 kA/contour) for a two disk cathode with $D = R_C - R_A = 5.5$ mm, $R_A = 0.5$ mm, $S = 5D = 27.5$ mm and $V \sim 500$ kV; b) l_{eff} versus S/D for above geometry. The line is simply a smooth curve drawn through the simulation points.

II. THE EXPERIMENT

Previous experiments on TriMeV had successfully used short 3-mm-thick cathodes at 1.5 to 2.5 MV to achieve good pinching on 0.5-mm-diameter anodes.[12] However, for the lower voltages required here, we believed that a longer cathode with enhanced I_{SCL} would be needed to achieve pinching early in the pulse.

A typical cathode used in TriMeV experiments with $R_C = 4$ mm and $R_A = 0.25$ mm is illustrated in Fig. 5. Although a variety of cathode lengths were fielded, only data from the longest and the shortest are discussed here. The longest cathode had four 0.5-mm-thick cathode disks each separated by 8 mm or about 2D. The shortest cathode had two 0.5-mm-thick cathode disks separated by 2 mm. Thus, $l_{eff} \sim 32$ mm for the longest cathode is about 3 times $l_{eff} \sim 10$ mm for the shortest cathode.

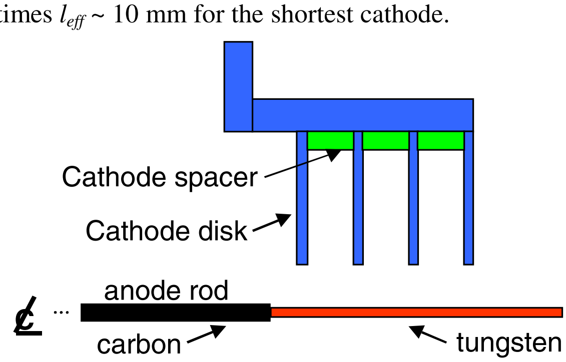

Figure 5. Typical TriMev rod pinch diode configuration.

The long cathode did lower the impedance early in time before I_{crit} was achieved, but the short cathode also worked well. We believe this is because the bipolar SCL current enhancement factor for large R_C/R_A, illustrated in Fig. 3a, allowed the short cathode to operate near critical current for most of the pulse duration. Figure 6a shows that early in the pulse, the long cathode exhibited a slightly lower voltage and higher current than the short cathode. Figure 6b illustrates that the impedances nearly overlay each other after I_{crit} is reached, demonstrating that I_{crit} is independent of l_{eff}.

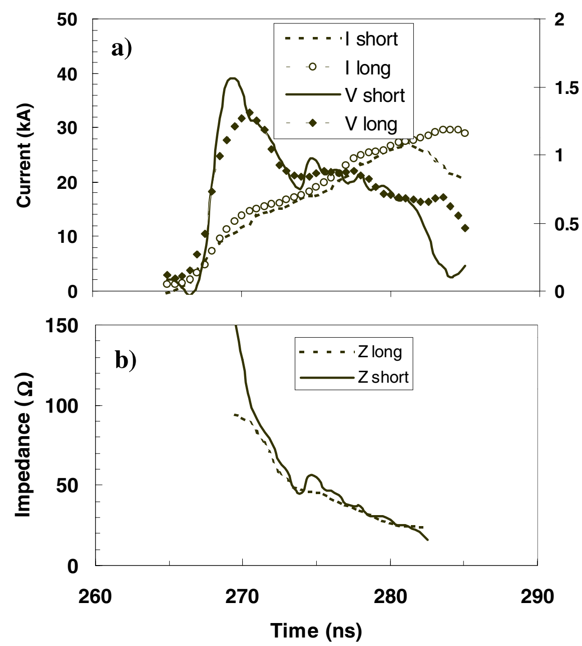

Figure 6. a) Voltage and current waveforms and b) impedance waveforms for long (shot 218) and short (shot 313) cathodes.

Radiation measurements using a LANL supplied 1-m-radius rolled edge showed that the spot size, defined as the FWHM of the line spread function, was about 0.5 mm diameter. At these lower voltages, the measured doses ranged from 0.3 to 0.5 Roentgen at 1 m through 1 cm of plastic.

A more detailed look at the data shows that the long cathode (Fig. 7a) did enhance I_{SCL} and cause an earlier transition to I_{crit}, but the short cathode (Fig. 7b) still operated at about I_{crit} for most of the pulse. In Fig. 7, I_{load} is the measured current, and the predicted current, I_{th}, is derived from $1/I_{th}^3 = 1/I_{SCL}^3 + 1/I_{crit}^3$. This phenomenological fit to I_{SCL} and I_{crit} is confirmed by PIC simulations.[8] With the long cathode, I_{SCL} quickly exceeds I_{crit} and the beam is observed to strongly pinch. With the short cathode, I_{SCL} is comparable to I_{crit} and side viewing x-ray pinhole camera images, not shown here, confirm that the beam is still reasonably well pinched. In model calculations[2] of I_{SCL} and I_{crit}, the cathode plasma velocity was assumed to be 2 cm/µs which is the same value used over a wide range of geometries. However, a

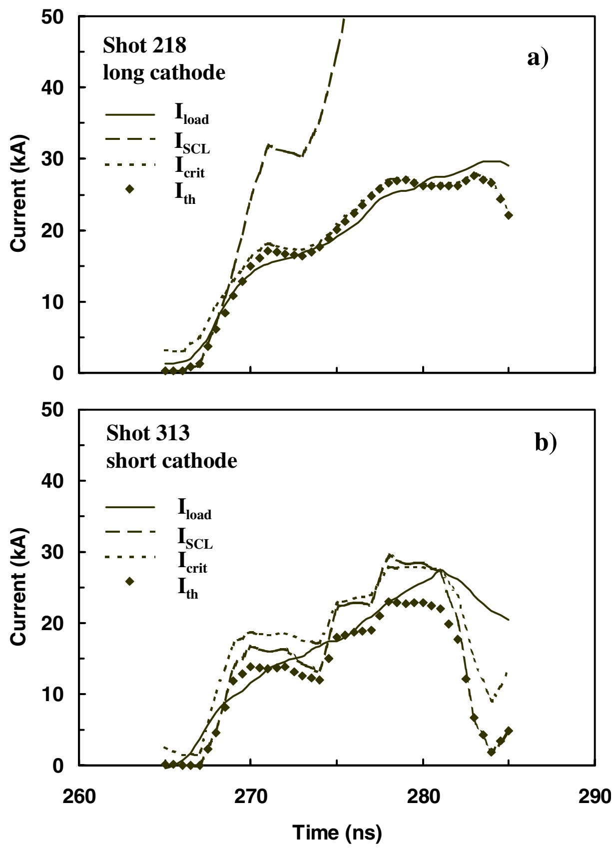

Figure 7. Measured load current, I_{load}, compared with calculated currents, I_{SCL}, I_{crit}, and I_{th} for a) long and b) short cathodes.

large anode plasma velocity of 3 cm/μs is required for these 0.5-mm-diameter tungsten anodes in order to properly fit the experimental current. After ions are allowed to turn on at 271 ns, the model assumes that it takes 10 ns for the ion effects on α and I_{SCL} to be fully felt. During this 10 ns, α increases from its electron-only value of 1.45 to its ion-enhanced value of about 3 and I_{SCL} increases from the electron only LB current to the ion-enhanced current. This 10 ns is needed to properly model the rising current waveform. For longer pulses, this 10 ns has an insignificant effect. This model has been shown to agree with a large set of data when a consistent set of physically-reasonable parameters are used.[2]

III. SUMMARY

In summary, large-aspect-ratio diodes enhance the bipolar SCL current and I_i/I_e over those obtained with planar diodes. Optimized multi-disk long cathodes were designed to enhance I_{SCL} in order to achieve an earlier transition to I_{crit} at low voltages. These long cathodes exhibited only slightly better pinching than short cathodes in TriMeV experiments at 800 kV and 15-ns pulse duration. We believe this is because the short-cathode bipolar SCL current was sufficiently enhanced for large R_C/R_A to approach critical current early in the pulse. Both long and short cathodes exhibit the same magnetically-limited operating impedance , illustrating that I_{crit} is independent of length. Source diameters were about 0.5 mm, comparable to the 0.5-mm anode diameter. Doses approached 0.5 Roentgen at 1 m. We believe that long cathodes will be needed to obtain tightly pinched electron beams at even lower operating voltages.

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